A novel noise model extraction technique for microwave and millimeter wave HEMT

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Abstract — **In this paper a novel method to extract the noise parameters of active devices up to millimeter wave frequencies is presented. The method is based on S-parameters and 50Ω noise figure measurements only; the extraction of the small-signal equivalent circuit model of the device is not required. The method may be applied to FET with low parasitic elements, e.g. devices having a coplanar layout. A brief description of the measurement set-up used to perform noise figure measurements is given. Lastly, the validity of the proposed technique is demonstrated applying it to a low noise HEMT device from NEC, and comparing the results with those of a more conventional method based on the full knowledge of the device small-signal equivalent circuit.**

I. INTRODUCTION

The complete noise characterization of an active device, necessary for the comparison of noise performances of different transistor technologies and for the design of low noise amplifiers, requires the knowledge of four real parameters, i.e. minimum noise figure (F_{min}), noise resistance (R_n) and optimum source admittance ($Y_{opt}=G_{opt}+jB_{opt}$). The noise figure for any source admittance, Y_s, may be expressed in terms of the four parameters above as:

$$F\left(Y_s\right)=F_{\min}+\frac{R_n}{G_s}\cdot\left|Y_s-Y_{opt}\right|^2 \qquad (1)$$

Two main methods are usually adopted to determine the four noise parameters: the first one [1] is based on a least square fit of (1) to, at least, four noise measurements. To reduce the problems due to measurements' inaccuracy more than four noise measurements are typically performed for different source admittances, making use of an electromechanical tuner. The second method [2] makes use of the noise temperature model of the device, that actually models the high-frequency device noise as equivalent thermal noise. The main advantage of the latter method resides in its simplicity, due to its dependence on two frequency-independent parameters (equivalent noise temperatures of the intrinsic gate resistance and drain conductance). The prediction of noise parameters in a broad frequency range is therefore possible performing two noise measurements only. On the other hand, a precise determination of the small signal equivalent circuit of the device under test is needed to obtain the noise performances.

Dambrine et al. [3]-[4] proposed an extraction procedure making use of an extrinsic equivalent circuit to reduce to three (instead of - at least - eight) the number of the equivalent circuit parasitic elements that have to be known: this method is effective for extrinsic source inductance L_s lower than 10 pH. Moreover, each parameter of the model proposed in [3] can be accurately deduced, up to W band, from S-parameter and noise measurements performed in lower frequencies (up to 40GHz).

In this paper a novel method to extract the noise parameters of field effect devices up to millimeter wave frequency range, based only on S-parameter and 50Ω noise figure (NF_{50}) measurements, is proposed. The extraction procedure is very fast if compared with the ones described in [2]-[3]: in fact, it doesn't need the S parameters measurements required for parasitic elements extraction; on the other hand, this procedure works only for devices presenting reduced parasitic effects.

To verify the validity of the proposed extraction technique the noise parameters of a low noise HEMT by NEC have been extracted. The results have been successfully compared with those obtained using a conventional method based on the full knowledge of the small signal equivalent circuit [5].

II. NEW EXTRACTION TECHNIQUE

The noise behaviour of a FET device can be described by a small-signal equivalent circuit including three noise voltage generators, which model the thermal noise added by the parasitic resistances (R_g, R_s, R_d), and two noise sources associated to gate (R_i) resistance and drain conductance (g_{ds}), as depicted in Fig.1.

The latter two intrinsic noise sources are modelled as equivalent thermal noise sources and described by two equivalent noise temperatures [2], T_{gs}, T_{ds}:

$$T_{gs}=\frac{\overline{i_{gs}}^2}{4kB}R_i \qquad (2)$$

$$T_{ds}=\frac{\overline{i_{ds}}^2}{4kBg_{ds}} \qquad (3)$$

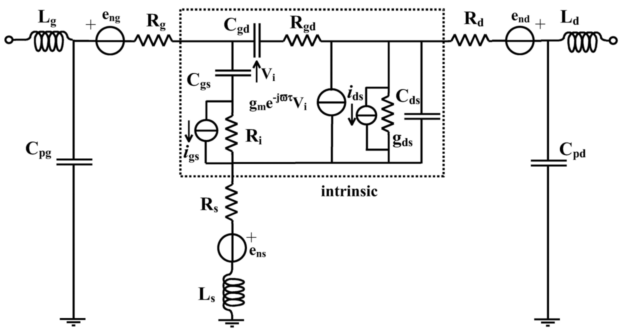

Fig. 1. Small-signal and noise equivalent circuit of the HEMT. The intrinsic part is boxed.

The intrinsic noisy circuit can be also represented by an admittance noise-free two port and two external current noise sources, as in Fig. 2; these may be expressed as functions of the intrinsic Y_{ij}^{int} parameters and the two internal noise current sources:

$$i_1 = R_{gs}\left(Y_{11}^{\text{int}} + Y_{12}^{\text{int}}\right) i_{gs} \tag{4}$$

$$i_2 = R_{gs}\left(Y_{21}^{\text{int}} - Y_{12}^{\text{int}}\right) i_{gs} + i_{ds} \tag{5}$$

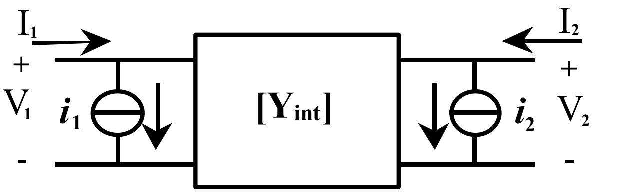

Fig. 2. The intrinsic noisy equivalent circuit of a FET may be represented by an identical, but noise free, [Y] two port, with two current noise sources at the input and the output of the network.

In addition, both gate resistance, R_i, and drain conductance, g_{ds}, may be expressed as a function of the intrinsic Y_{ij}^{int} parameters:

$$R_{gsi} = \text{Re}\left[\frac{1}{Y_{11}^{\text{int}} + Y_{12}^{\text{int}}}\right] \tag{6}$$

$$g_{ds} = \text{Re}\left[Y_{22}^{\text{int}} + Y_{12}^{\text{int}}\right] \tag{7}$$

Therefore, the admittance correlation matrix, C^Y [6], is completely described by the Y parameters of the intrinsic circuit and the equivalent noise temperatures:

$$C_{ij}^{Y} = \frac{1}{4kT_0B}\left\langle i_i \cdot i_j^* \right\rangle = C_{ij}^{Y}\left(Y_{ij}^{\text{int}}, T_{gs}, T_{ds}\right) \tag{8}$$

where i=1,2, j=1,2, k is the Boltzmann constant, T_0 is the standard noise temperature (290K), and B is the frequency bandwidth.

For active devices presenting low parasitic effects the elements of the noise admittance correlation matrix can be expressed with the functional form of the intrinsic ones, where the Y_{ij}^{int} are replaced by Y_{ij}^{extr}:

$$C_{extr}^{Y} \simeq C_{\text{int}}^{Y}\left(Y_{ij}^{extr}, T_{gs}, T_{ds}\right) \tag{9}$$

The noise figure of the device is a linear function of its chain correlation matrix [6]:

$$F\left(Y_s\right) = 1 + \frac{\left|Y_s\right|^2 C_{11}^T + 2\,\text{Re}\left(C_{12}^T Y_s\right) + C_{22}^T}{4kT_0G_sB} \tag{10}$$

On the other hand, using (9), C_{ij}^T depends on the Y parameters of the extrinsic device and the equivalent noise temperatures, T_{gs} and T_{ds}. Equation (10) may be used to obtain an overdetermined linear system of equations:

$$[A_i][T] = [\text{b}_\text{i}] \qquad i = 1,......,M \tag{11}$$

where M is the number of measured frequency points, $[T] = \begin{bmatrix} T_{gs} & T_{ds} \end{bmatrix}$, $b_i = 4kT_0\Delta f \cdot \left(F\left(Y_s^i\right) - 1\right) G_s^i$, $A_i = A\left(Y_{ij}^i\right)$ and Y_{ij}^i are the measured Y parameters of the device. A least square fitting procedure allows the determination of the equivalent noise temperatures and the noise parameters:

$$R_n = C_{11}^T \tag{12}$$

$$Y_{opt} = \sqrt{\frac{C_{22}^T}{C_{11}^T} - \left(\frac{\text{Im}\left(C_{12}^T\right)}{C_{11}^T}\right)^2} + j\frac{\text{Im}\left(C_{12}^T\right)}{C_{11}^T} \tag{13}$$

$$F_{\min} = 1 + 2\left(C_{12}^T + C_{11}^T Y_{opt}^*\right) \tag{14}$$

III. MEASUREMENT SET-UP

Fig. 3 shows the on-wafer noise figure measurement set-up, composed by a noise source up to 40 GHz (NC-346 KA), a probe station (RF-1 Cascade-Microtech), two bias-tees, an isolator, a LNA and a Noise Measurement System (NMS) up to 40 GHz.

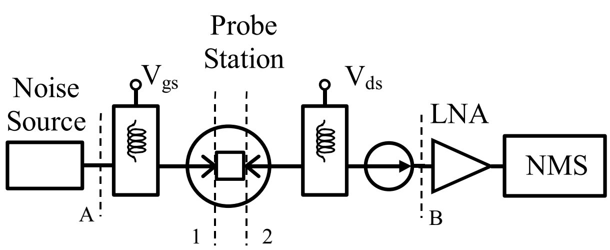

Fig. 3. On-wafer noise figure measurement set-up.

Both isolators and LNA are narrow-band devices to obtain a good isolation and low noise figure of the receiver respectively. The NMS is made up of HP8970B-

HP8971C for measurements up to 26GHz; to extend the measurement frequency up to 40 GHz, the HP8971C is replaced by a home-made SSB down converter. A Vector Network Analyzer (HP8510C) is used for S-parameter measurements up to 50 GHz. The calibrated ENR (plane A) is translated on wafer (plane 1) [7]; then, connecting planes 1 and 2 with a coplanar thru-line, the NMS calibration is performed; lastly, the thru-line is replaced with a DUT and noise figure measurements are performed. A vector correction of the noise figure of the NMS is performed off-line using the S parameters of the passive two-port network between plane 2 and plane B [8].

IV. EXPERIMENTAL RESULTS

To validate the proposed method, the noise parameters of the pseudomorphic coplanar low noise HEMT NE321000 manufactured by NEC, have been extracted, for different bias conditions, using the novel technique and the conventional one [2].

For this purpose, the S parameters of the device have been measured under active and cold-FET bias conditions to determine its small signal equivalent circuit [9]. NF_{50} measurements are also performed at the same active bias points. The extracted equivalent circuit and the noise measurements have been used to determine the noise parameters of the active device, using the method in [2].

In Fig. 4-5 measured and modelled S-parameters are compared, in the frequency range 1-40 GHz.

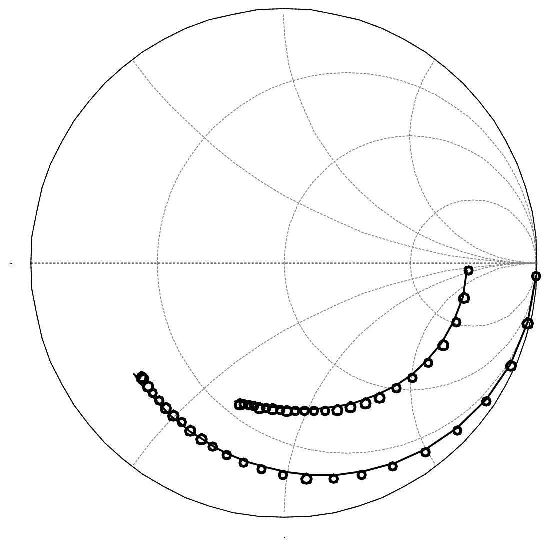

Fig. 4. Measured (○) and modelled (–) S_{11} and S_{22} parameters for the NEC device in the 1-40GHz frequency range at V_{ds}=2V, I_{ds}=10mA.

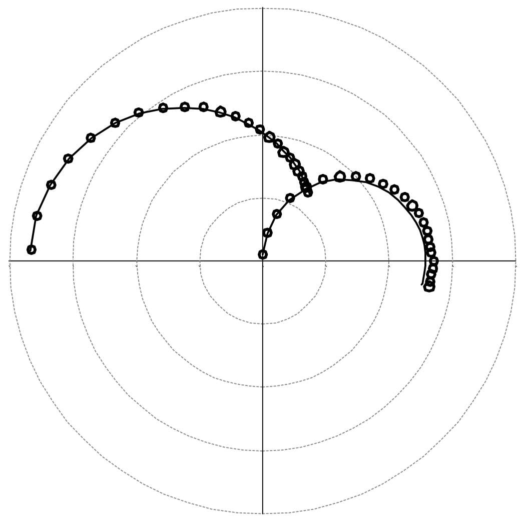

Fig. 5. Measured (○) and modelled (–) S_{12} and S_{21} parameters for the NEC device in the 1-40GHz frequency range at V_{ds}=2V, I_{ds}=10mA. The S_{21} and S_{12} radii are 3 and 0.2, respectively.

The measured NF_{50} of the device biased at V_{ds}=2V and I_{ds}=0.25 I_{dss}, in the frequency range 2-35 GHz, is shown in Fig.6.

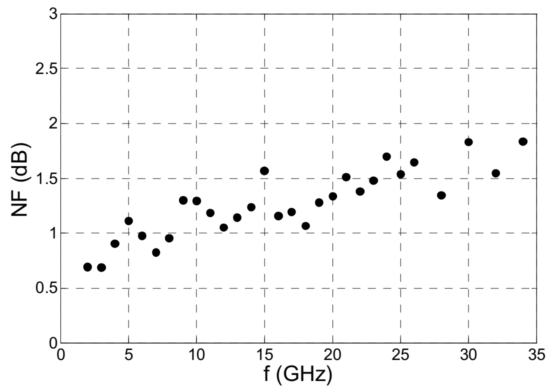

Fig. 6. Measured NF50 for the NEC device in the 2-35GHz frequency range at Vds=2V, Ids=10mA.

The S parameter and NF_{50} measurements have been used to determine the noise parameters applying the novel technique.

A comparison between the results of the two methods is shown in Fig.7,8,9,10 for two different bias conditions. A good agreement can be observed in the results of the two different methods up to 25 GHz; for upper frequencies the effects of the parasitic elements appear clearly, regarding in particular the phase of the optimum source load.

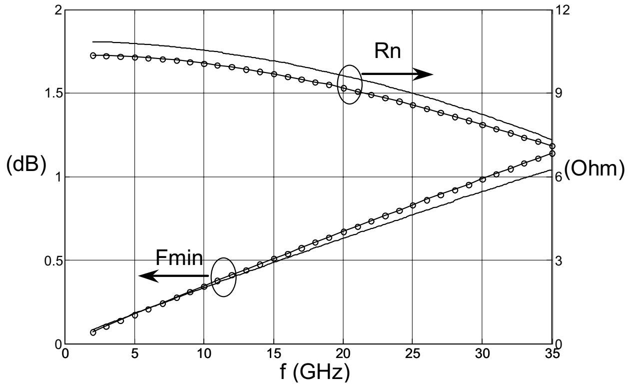

Fig. 7. Noise parameters comparison extracted using the proposed method (–) and the equivalent noise temperatures model (○) for the NEC 321000 HEMT at V_{ds}=2V, I_{ds}=10mA.

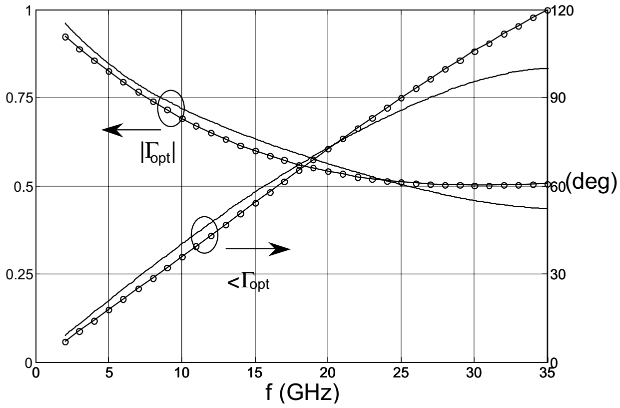

Fig. 8. Noise parameters comparison extracted using the proposed method (–) and the equivalent noise temperatures model (○) for the NEC 321000 HEMT at V_{ds}=2V, I_{ds}=10mA.

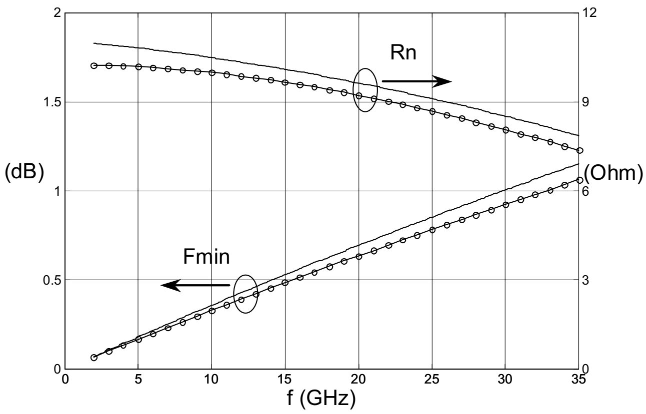

Fig. 9. Noise parameters comparison extracted using the proposed method (–) and the equivalent noise temperatures model (○) for the NEC 321000 HEMT at V_{ds}=2V, I_{ds}=20mA.

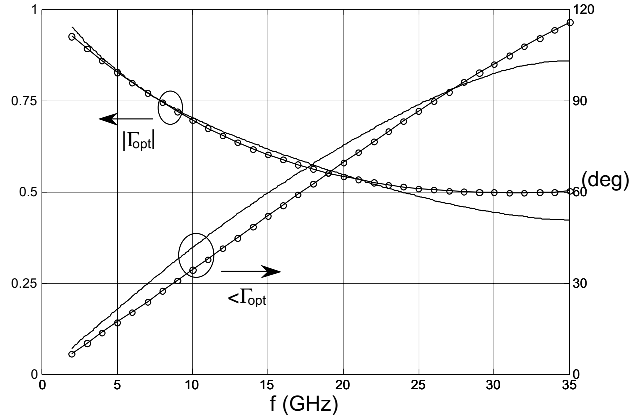

Fig. 10. Noise parameters comparison extracted using the proposed method (–) and the equivalent noise temperatures model (○) for the NEC 321000 HEMT at V_{ds}=2V, I_{ds}=20mA.

V. CONCLUSIONS

A novel technique to determine the noise parameters of an active device has been proposed. The method utilizes S parameters and NF_{50} measurements only and it doesn't require any small-signal equivalent circuit extraction. The proposed technique has been applied to a coplanar low noise HEMT manufactured by NEC, and has been validated by a comparison with a more conventional method [2].

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